

pivots about a point on the stylus or stem some distance away from the pickup plate. This causes an undesired translational motion in addition to the desired rotational response for x and y axis displacement of the stem. This undesired translational response may generate undesired cross-axis readings. For instance, a pure x-axis displacement of the stem may produce a false Z-axis reading. The other problem is that the signal channels are separated from each other by operating at different frequencies. This results in the individual channels having different noise and frequency response characteristics, which is generally undesirable for precision measurements.

Precision capacitive displacement transducers typically employ three electrodes, which form a structure equivalent to two capacitors connected in series, with the center electrode being movable and common to both capacitors. The center electrode is also *E Picks-up]* typically the pickup electrode, and the two outer electrodes are mechanically fixed. Although the transducer is fundamentally responsive to displacement of the center electrode, it can be used to measure force, by the deflection of springs of known stiffness in response to that force, as well as acceleration or pressure. Bonin et al. (US Pat. No. 4,694,687) discloses a vehicle performance analyzer which incorporates a capacitive accelerometer based on the three electrode structure described here. By driving the outer electrodes with two equal amplitude signals 180 degrees out of phase, the voltage on the center electrode is a linear function of the displacement from the center, with the phase giving polarity information. The full scale amplitude of the output

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## BRIEF SUMMARY OF THE INVENTION

The present invention provides a force or displacement transducer operative in at least two nominally orthogonal directions in a first embodiment. In a second embodiment, the transducer of the first embodiment is incorporated into an apparatus for measuring mechanical properties of MEMS devices or other small devices, hardness and scratch resistance of thin films and surfaces, and friction and wear properties of small components such as sliders used in the disc drive industry.

The transducer consists of a centrally located plate shaped pickup electrode, also referred to as the center electrode or as the pickup plate and several pairs of drive plates on opposing sides of the pickup plate. Preferably there are four pair of drive plates. The drive plates are of a conductive material, which may be copper, fabricated on an insulating substrate for mechanical support using techniques well known in the printed circuit board industry. The center electrode is also formed of a conductive material, but preferably of higher strength than pure copper, such as a high strength Beryllium copper alloy. Support springs for maintaining the proper position of the center electrode are formed integrally with the center electrode by photochemical etching which is a well known process. By arranging the support springs to connect to the center electrode in the same plane as the center electrode, rather than connect to the load stem at some point away from the center electrode, undesired lateral motion of the center electrode which could generate erroneous cross axis signals is eliminated. This also allows for more convenient electrical connection to the moving center electrode, by using the fixed end of one or more of the springs <sup>[at]</sup> as the electrical contact.

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signal is decreased when the electrode plates are not parallel to each other. In both the current invention, and in Thomas, X or Y axis forces cause the center electrode to rotate out of parallel, but the effect on linearity is less severe in the current invention, since the Z-axis ring electrode of Thomas is eliminated. By eliminating the ring, and using only the four quadrant electrodes, the effect of the center electrode tilt is reduced, as the active drive plate covers only about 1/3 of the width of the center electrode, reducing the effect of the tilt on the linearity by the same factor.

The multi-dimensional capacitive transducer has many applications, including use in an instrument for tribological property testing, and also mechanical testing of small structures such as MEMS devices. The tribological property tester consists of a mechanism to provide relative motion between two samples being tested, with one of the samples being mounted on the multi-dimensional capacitive transducer. This provides reading of both the normal (Z-axis) load force and the resultant frictional force, so that friction coefficient vs load force, time, speed and other parameters can be readily determined. For testing MEMS devices, the device to be tested is mounted on a moveable stage, which could be a stage on an optical microscope. The multi-dimensional capacitive transducer is mounted above the device to be tested. If the stage just referred to is on an optical microscope, the transducer may be mounted in place of one of the optical objectives. This allows the device to be tested to be optically inspected and positioned, so that when the turret is rotated to engage the multi-dimensional capacitive transducer, the probe stem mounted on the transducer

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The electrode patterns are formed by standard printed circuit board processing techniques.

If higher cost is permissible in return for better mechanical and thermal stability, the drive plate electrode assemblies <sup>[a NR]</sup>11 and 16 may alternately be fabricated on an aluminum oxide substrate, using well known hybrid circuit fabrication techniques. In this case, to achieve the desired thermal stability, it is important that the spacers 12, 14 and the center electrode assembly 13 be fabricated of a material with a thermal expansion coefficient similar to the aluminum oxide substrate, such as Molybdenum metal.

The preferred method of assembling transducer assembly 10 is to coat spacers 12, 14 with a thin layer of adhesive such as epoxy, assemble the five main elements as shown in Fig. 1 and hold them together under pressure until the adhesive is cured.

Fig. 8 is a perspective view of one corner of the center electrode assembly 13 and the two spacers 11 and 16, showing the detail of the end support of spring element 22. The spacers 11, 16 do not cover all of the spring support structure 21, but leave the region at the base of the spring exposed. The purpose of this is to reduce the stress to which the adhesive bond is exposed. The purpose of the additional triangular support regions 48 of the center electrode, 47, 49 of the two spacers and 46, 50 of drive plate assemblies is to increase the area of the adhesive bond to further reduce the stress in the bond line. Minimizing the stress in the adhesive bond line is extremely important in a precision transducer, because polymeric materials, such as epoxies and other adhesives, will begin to deflect and creep

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would not be consistent as the contact geometry would vary from test to test .

Referring to Figs. 1- 7 as required, the operation of the transducer will now be explained. Although the actual circuitry used in this invention adjusts the drive plate voltages to maintain zero output voltage on the center electrode, for simplicity, consider for now the case with a fixed, equal AC voltage on all drive plates, but with the phase between the upper and lower drive plates being 180 degrees different. Without an applied load to the end of probe assembly 55, the springs 22 are undeflected and the center electrode 23 is equidistant between the lower drive plates X2, X4, Y2, Y4 and the upper drive plates X1, X3, Y1, Y3. This represents a null condition, with no signal being present on the center electrode 23. Now consider a load force applied to the probe 55 in the vertical, Z-axis direction. Springs 22 will bend equally, and center electrode 23 will deflect upwards toward the upper drive plates and away from the lower drive plates. The center electrode will then pick up more signal from the upper drive plates since it is closer to them, and less from the lower drive plates, resulting in AC signals on the center electrode proportional to the amount of displacement, and with a phase dependent on the direction of the displacement. If the drive plate voltages were constant the linear output signal would result from using a high input impedance buffer rather than charge amplifier 91 to amplify the signal generated on center electrode 23. Either way, the buffered and/or amplified AC signal at the output of amplifier 91 is synchronously demodulated and <sup>[multiplexed]</sup> demultiplexed to separate the signals into four separate differential channels by eight channel analog multiplexer

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The fourth used output of 82, Y6, controls drive plate pair Y3, Y4. The timing diagram, Fig 10, shows the sequencing of these drive plate signals graphically versus time. The voltage levels of the pulses to drive plates X1, X2, X3, X4 assume a certain deflection of the load stem in the X-axis, with the circuit operating in a feedback mode that will be explained later.

Eight channel analog <sup>[multiplexer]</sup> demultiplexer 96 is controlled by the same binary count sequence generated by counter 81 as is decoder 82. The least significant bit of counter 81 is connected to the disable input of multiplexer 96 to reduce the duration of the sample time to half of the drive plate pulse time. Inverter 83 is used to set the correct phase, so that the first sample period for a given drive plate pair is during the last half of that drive plate pulse, to avoid transient signals due to the switching at the beginning of the pulse. The transients generated at the end of the pulse are likewise avoided by the second sampling period being delayed in the same manner. This sample window for multiplexer 96 is shown in Fig. 10, and is labeled CH1A Enable, CH1B Enable, through CH4A Enable, CH4B Enable. Note that the channel enable signals are not accessible, but are generated internally to <sup>[multiplexer]</sup> demultiplexer 96 and are shown to help in understanding the operation of the circuit.

It should now be possible to understand how the separate channel information is obtained from the single pickup plate e.g., electrode 23 and four pair of drive plates. Referring to Fig. 10, but assuming no feedback to the drive plates, with the upper drive plates X1, Y1, X3, Y3 being pulsed from -5V to zero and the lower drive plates X2,

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The binary counter 81 may be an industry standard 74HC161, and the decoder 82 may be a 74HC138. The multiplexers 86, 87, 88 may be of type 74HC4053 and the eight channel *multiplexer* demultiplexer 96 may be a type 74HC4051. Amplifier 92 must be of high enough speed for the operating clock frequency of oscillator 76, and should generally be a precision, low noise high speed device. An LT1363 from Linear Technology Corporation is a good choice. The value of resistor 93 must supply the required DC bias current to the negative input terminal of amplifier 92, without discharging capacitor 94 significantly during the duration of one drive plate pair pulse. A value of 1,000,000 Ohms is suitable. Charge integration capacitor 94 should be on the same order as the transducer capacitance. A value of 22pF was found to work satisfactorily with a transducer of overall size one inch square and plate spacing of 0.006 inch.

The value of the sample capacitors 97, 98, 101, 102, 106, 107, 111, 112 are not critical and can be on the order of 0.01 $\mu$ F. The differential amplifiers 99, 103, 108, 113 may be single integrated devices as shown in Fig. 9b, or they may be constructed from operational amplifiers and resistors using one of several possible configurations which are familiar to those skilled in the art of analog electronic circuitry.

The electrical connections from the circuitry to the transducer drive plates and center electrode have not been shown in the transducer figures as there are a number of different possibilities for doing so that are well known to those skilled in the electronics circuit field, and to avoid unnecessarily complicating the figures. The preferred method of making the connections is to use industry standard plated through

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## ABSTRACT

A high precision force and displacement measuring device adapted to operate in at least two directions, including signal multiplexing scheme providing multiple signal channels to be transmitted through a single <sup>[pick-up plate]</sup> pickup electrode and sense amplifier, while maintaining high isolation between the channels, as well as identical electrical response characteristics of all channels. The device may be used in conjunction with a movable stage (such as on an optical microscope) to perform mechanical measurements on Micro Electro-Mechanical Systems (MEMS) devices.

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